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Trend discrepancies among three best track data sets of western North Pacific tropical cyclones

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[1] The hot debate over the influence of global warming on tropical cyclone (TC) activity in the western North Pacific over the past several decades is partly due to the diversity of TC data sets used in recent publications. This study investigates differences of track, intensity, frequency, and the associated long-term trends for those TCs that were simultaneously recorded by the best track data sets of the Joint Typhoon Warning Center (JTWC), the Regional Specialized Meteorological Center (RSMC) Tokyo, and the Shanghai Typhoon Institute (STI). Though the differences in TC tracks among these data sets are negligibly small, the JTWC data set tends to classify TCs of category 2–3 as category 4–5, leading to an upward trend in the annual frequency of category 4–5 TCs and the annual accumulated power dissipation index, as reported by Webster et al. (2005) and Emanuel (2005). This trend and potential destructiveness over the period 1977–2007 are found only with the JTWC data set, but downward trends are apparent in the RSMC and STI data sets. It is concluded that the different algorithms used in determining TC intensity may cause the trend discrepancies of TC activity in the western North Pacific.

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1. Introduction

[2] In recent years, there has been increasing interest in whether global warming is enhancing tropical cyclone (TC) activity [*Chan*, 2005; *Emanuel*, 2005; *Webster et al.*, 2005; *Landsea*, 2005, 2007; *Anthes et al.*, 2006; *Curry et al.*, 2006; *Hoyos et al.*, 2006; *Holland and Webster*, 2007; *Vecchi et al.*, 2008]. Though some studies suggested that the reported trends in TC activity were related more to the local effect of warming sea surface temperature (SST) over the past several decades [*Emanuel*, 2005; *Webster et al.*, 2005; *Hoyos et al.*, 2006; *Mann and Emanuel*, 2006; *Santer et al.*, 2006; *Elsner*, 2006; *Emanuel*, 2008], there are many studies arguing that these trends may result from discrepancies in TC data sets themselves [*Landsea*, 2005, 2007; *Pielke*, 2005; *Pielke et al.*, 2006; *Klotzbach*, 2006; *Vecchi and Knutson*, 2008]. One reason, among others, is that the TC best track data were insufficiently reliable for detecting trends in TC activity, in particular before the 1970s, when satellite data were not available for determining the TC intensity [*Emanuel*, 2008].

[3] The annual number of TC (tropical storms and typhoons) formation is about 27 in the western North Pacific (WNP) basin, which accounts for 33% of the total TCs in the world [*Chan*, 2005]. *Wu et al.* [2006] and *Yeung* [2006] examined the best track data from the Regional Specialized Meteorological Center (RSMC), Tokyo, Japan, as well as that of the Hong Kong Observatory of China (HKO), indicating that, in contrast to *Webster et al.* [2005], there was no increase in category 4–5 typhoon activity in the WNP basin. Moreover, neither RSMC nor HKO best track data suggest an increase in TC destructiveness as measured by the potential destructive index that is the same as the power dissipation index (PDI) [*Wu et al.*, 2006]. Other studies also examined the differences in TC data sets from the Joint Typhoon Warning Center (JTWC) of U.S. Naval Pacific Meteorology Oceanography Center in Hawaii (in Guam before 1999), the RSMC, and the Shanghai Typhoon Institute (STI) of China Meteorological Administration in Shanghai [*Lei*, 2001; *Kamahori et al.*, 2006; *Ott*, 2006; *Yu et al.*, 2007]. So far, the reported trends in TC activity in the WNP basin have been detected mainly in the JTWC best track data set [*Webster et al.*, 2005; *Emanuel*, 2005].

[4] Two reasons may account for these different analysis results. One is that these organizations often reported different intensities for the same TCs since different time intervals or different algorithms are used to estimate the average maximum sustained wind [*Yu and Kwon*, 2005; *Wu et al.*, 2006]. The maximum sustained wind in the RSMC data set has been averaged over a 10 min period since 1977, while it is averaged over a 2 min period in the STI data set and over a 1 min period in the JTWC data set. The other reason is that the TC records in these data sets are not exactly the same. A TC may be missed in one data set when

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Table 1. Tropical Cyclone Intensity Categories in the Western North Pacific, 1949–2007

Shanghai Typhoon Institute (STI) Scale			Saffir-Simpson Scale	VMAX ($m\ s^{-1}$)	MSLP (hPa)
1949–1988	1989–2005	2006–2007			
tropical depression	tropical depression	tropical depression	tropical depression	<17.2	…
typhoon	tropical storm	tropical storm	tropical storm	17.2–24.2	…
typhoon	severe tropical storm	severe tropical storm	tropical storm	24.3–32.5	…
severe typhoon	typhoon	typhoon	category 1 typhoon	32.6–42.1	>980
severe typhoon	typhoon	severe typhoon	category 2 typhoon	42.2–48.8	965–980
severe typhoon	typhoon	super typhoon	category 3 typhoon	48.9–58.1	945–965
severe typhoon	typhoon	super typhoon	category 4 typhoon	58.2–69.4	920–945
severe typhoon	typhoon	super typhoon	category 5 typhoon	>69.4	<920

it appeared in the others. This may seriously compromise the comparison results.

[5] Previous studies that compared TC best track data sets were mostly focused on the differences of individual TCs [*Yu and Kwon*, 2005; *Lander and Guard*, 2006], TCs in some subbasins [*Leung et al.*, 2007], TC activity in a few years [*Ott*, 2006], and the long-term trends of TC activity (by including all the TCs) [*Wu et al.*, 2006; *Yeung*, 2006; *Yu et al.*, 2007]. In contrast to previous research, our objective in this study is to examine the differences in track and intensity only for those TCs that were recorded simultaneously in the JTWC, RSMC, and STI best track data sets from 1945 to 2007. In particular, the following issues are addressed: Does the difference in estimating maximum sustained wind within different average periods mainly account for the difference in TC intensity? Do the trend differences of annual TC frequency and potential destructiveness reported in previous studies still exist for the simultaneously recorded TCs (hereafter concurred-TCs) in the three data sets? The rest of the paper is organized as follows. The information about the three data sets and techniques of locating track and determining intensity is described in section 2; the differences of track and intensity among these data sets are estimated in section 3, followed by an analysis of the trends in the annual numbers of different categories and PDI during the period 1977–2007 in section 4; the main conclusions are presented in section 5.

2. Estimating Techniques and Data

[6] As mentioned above, the best track TC data sets used in this study are obtained from JTWC (available at https://metocph.nmci.navy.mil/jtwc/), RSMC (available at http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/), and STI (available at https://www.typhoon.gov.cn). Although the sources of reconnaissance (e.g., aircraft, satellite, radar, and synoptic data) vary from one basin to another, the observational data used in the JTWC, RSMC, and STI are almost the same in locating track and estimating intensity in the WNP basin. Before the 1970s, aircraft reconnaissance was the dominant method used to locate the center and determine the intensity. Radar data were used only when a TC was within the radar range. Satellite data were used primarily as the basis for scheduling aircraft investigative flights, because its interpretation of TC-related information was not sufficiently accurate for operational use. Until 1971 satellite data were not used operationally to estimate intensity and center location at the JTWC. The proportion of satellite-derived data in TC reconnaissance became more and more important after the Dvorak technique (hereafter DT) [*Dvorak*, 1972, 1973] was advanced. In 1977, for the first time more than half of JTWC warnings in the WNP (51%) were based on satellite reconnaissance data. In the same year, RSMC started to record the maximum sustained winds (hereafter referred to as VMAX) with the DT.

[7] Now the DT is used by all three organizations but their details are different. At JTWC, the original DT [*Dvorak*, 1975] was used for determining TC position and intensity with visible and infrared satellite imagery (see http://www.usno.navy.mil/JTWC/annual-tropical-cyclone-reports). The improved methods such as the objective Dvorak technique [*Velden et al.*, 1998] and advanced objective Dvorak technique [*Olander and Velden*, 2007] are also used. At RSMC, the original DT was utilized until 1990. The new technique is based on the improvements described by *Koba et al.* [1990] by relating the WNP reconnaissance data (1981–1986) to the 10 min wind [*Nakazawa and Hoshino*, 2009]. In contrast to these two organizations, the original DT was amended by considering some regional synoptic characteristics for operational use in STI [*Fang and Zhou*, 1980]. Two important improvements were made for using enhanced infrared imagery in 1990 and for applying digital satellite imagery in 1996 [*Jiang*, 1986; *Fan et al.*, 1996].

[8] In addition to the different estimating techniques, the information recorded in the three data sets also differs in detail. The JTWC data set ranges from 1945 to 2007 while the RSMC and STI data sets cover the periods 1951–2007 and 1949–2007, respectively. These data sets contain the latitude and longitude of cyclone centers, and the intensity measured by VMAX and/or central sea level pressure (hereafter MSLP). Note that the MSLP is included in the JTWC data set only after 2000. As shown in Table 1, the TC intensity in the JTWC data set is categorized by the Saffir-Simpson scale based on the 1 min average VMAX whereas three intensity scales in the STI data set were used to categorize TCs for the periods 1949–1988, 1989–2005, and 2006–2007, respectively, based on the 2 min average VMAX.

[9] Since tropical depressions (VMAX < 17.2 $m\ s^{-1}$) are not included in the RSMC data set, we only examine those concurred-TCs with a VMAX larger than 17.2 $m\ s^{-1}$. Figure 1 shows the annual numbers of TCs in each data set and the concurred-TCs (vertical bars). The concurred-TCs account for 94%, 92%, and 88% of all TCs in the JTWC, RSMC, and

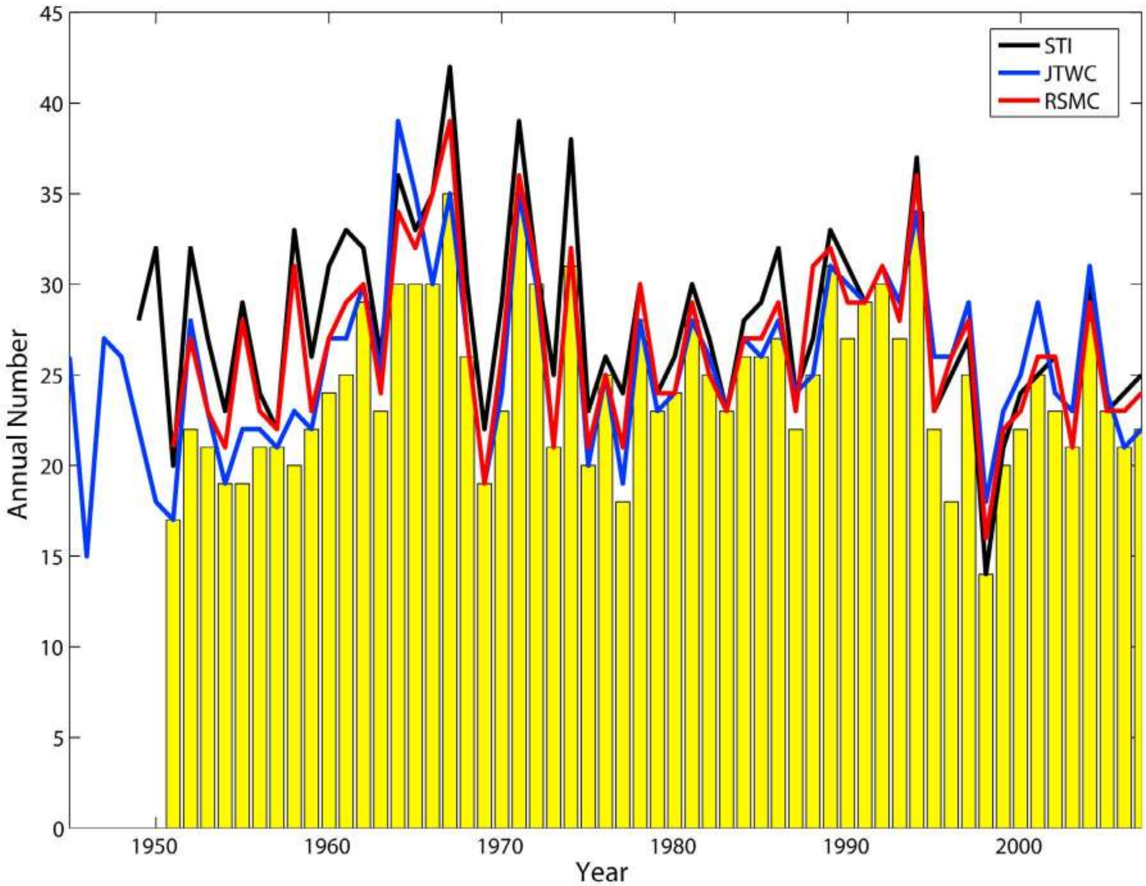

Figure 1. Annual number of tropical storms and typhoons over the western North Pacific from 1945 to 2007 as compiled by the Shanghai Typhoon Institute (STI) (1949–2007, black curve), Joint Typhoon Warning Center (JTWC) (1945–2007, blue curve), and Regional Specialized Meteorological Center (RSMC) (1951–2007, red curve). Also plotted are the simultaneously recorded tropical cyclones (concurred-TCs) for the period 1951–2007 (yellow bars) identified from the three data sets, accounting for 88%, 94%, and 92% of tropical storms and typhoons in the STI, JTWC, and RSMC data sets, respectively.

STI data sets, respectively, indicating that they are dominant in all three data sets.

3. Differences in TC Center Position and Intensity

[10] To analyze the differences of TC track and intensity among the three data sets, whose accuracy could be affected by the estimating technology change [cf. *Guard et al.*, 1992], two indices are defined as follows:

$$\Delta P = r_0 \cdot \cos^{-1}\{\sin(\varphi_1)\cdot\sin(\varphi_2)+\cos(\varphi_1)\cdot\cos(\varphi_2)\cdot\cos(\lambda_1-\lambda_2)\}, \quad (1)$$

$$\Delta V = \mathrm{VMAX}_1 - \mathrm{VMAX}_2, \quad (2)$$

where ΔP is the difference of the TC center position between data sets 1 and 2, which is measured using the distance between two geographic points (λ_1, φ_1) and (λ_2, φ_2) on the Earth surface. The λ and φ are the longitude and latitude of the TC center, respectively; r_0 is the radius of the Earth (6.4×10^3 km). ΔV is the VMAX difference between data sets 1 and 2.

[11] Figure 2 shows the average annual differences of center positions (ΔP) and intensities between any two of the data sets. In general, ΔP is less than 30 km. The positional differences decrease without an abrupt change in the 1980s, indicating that the positioning accuracy has been gradually improved over the WNP basin. The smallest difference occurs between the RSMC and STI data sets.

[12] The absolute intensity difference ($|\Delta V|$) between the STI and JTWC data sets and between the RSMC and JTWC data sets has increased since 1977 (Figure 2), suggesting that the annual average TC intensity in the RSMC and STI data sets was increasingly weaker than that in the JTWC data set. The maximum intensity difference occurred in the mid-1990s, exceeding 10 m s^{-1}. On the other hand, the intensity difference between STI and RSMC was the smallest and decreased with time. As suggested by *Wu et al.* [2006], the intensity difference among some data sets may be due to the differences in estimating techniques and algorithms (e.g., DT). Moreover, the increasing trends in

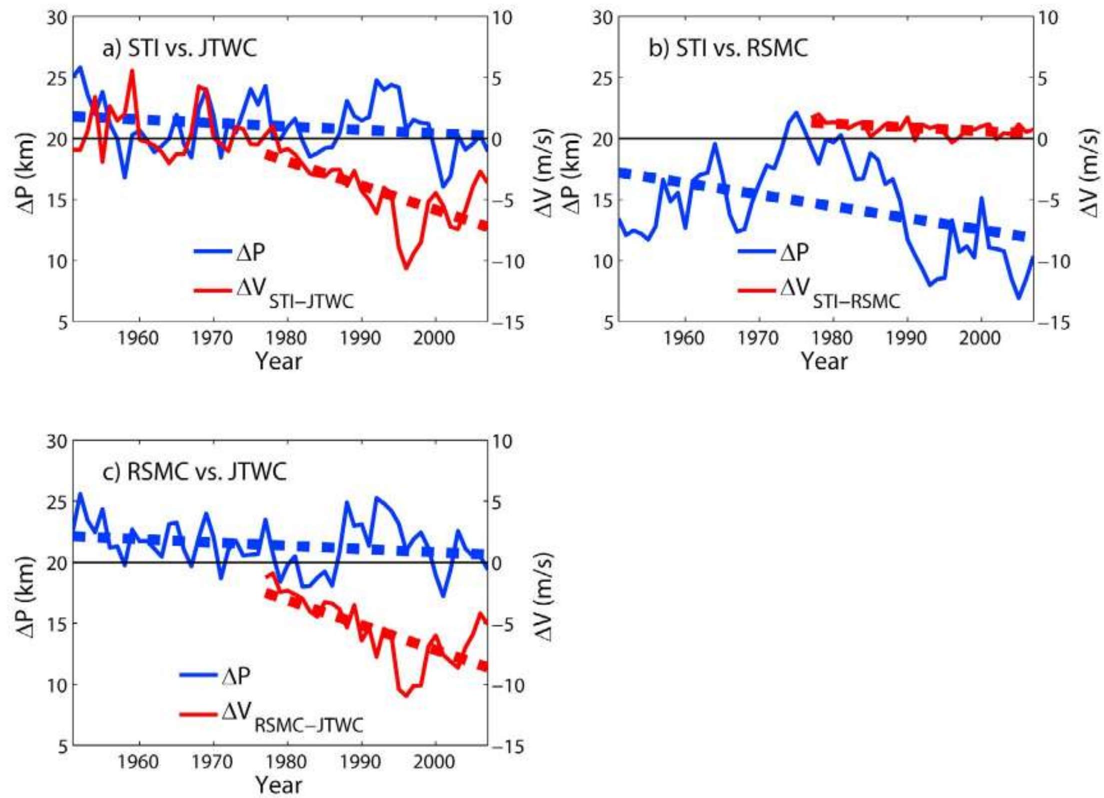

Figure 2. Annual average differences (solid curves) of TC center position (ΔP) and intensity (ΔV) between 1951 and 2007, where dashed lines refer to the trends of ΔP (1951–2007) and ΔV (1977–2007), which are statistically significant at the 5% level based on *F* tests. The negative ΔV means weaker STI intensity in Figure 2a and 2b and weaker RSMC intensity in Figure 2c.

intensity difference in Figures 2a and 2b are hardly explained by the estimating technique itself because the intensity bias should decrease with the improvement in TC-observing technologies. The different time periods for averaging also cannot account for the increasing trends in intensity difference. Therefore we suggest that the diversity in VMAX-estimating algorithms may be a major reason.

[13] To further explore intensity differences among the three data sets, Figure 3 shows the VMAX difference for all concurred-TCs, indicating that VMAX in one data set can be greater or weaker than that in another data set. For example, when $VMAX_{STI}$ equals 40 m s^{-1}, $VMAX_{JTWC}$ and $VMAX_{RSMC}$ can be 15~70 m s^{-1} and 18~50 m s^{-1}, respectively (the subscript indicates the data set). The statistical relationships can be obtained through least squares regression fitting as follows:

$$VMAX_{STI} = 1.98 \cdot VMAX_{JTWC}{}^{0.78} \cdot (2\text{ min versus }1\text{ min}), \quad (3)$$

$$VMAX_{RSMC} = 2.56 \cdot VMAX_{JTWC}{}^{0.70} \cdot (10\text{ min versus }1\text{ min}), \quad (4)$$

$$VMAX_{STI} = 0.85 \cdot VMAX_{RSMC}{}^{1.05} \cdot (2\text{ min versus }10\text{ min}). \quad (5)$$

The relationships indicated by the red lines in Figure 3 are all statistically significant at the 5% level based on the *F* test. Here we did not convert VMAX that is averaged over different periods into VMAX in a single average time by multiplying a constant [*Kamahori et al.*, 2006; *Kruk et al.*, 2008] because the VMAX relationship between any two data sets is nonlinear, as discussed later.

[14] When TCs reach the TY (VMAX $\geq$ 32.6 m s^{-1}) strength, $VMAX_{STI}$ is generally weaker than $VMAX_{JTWC}$ (Figure 3a) and greater than $VMAX_{RSMC}$ (Figure 3c). That is, $VMAX_{JTWC} > VMAX_{STI} > VMAX_{RSMC}$. The relationships suggest that the TY intensity in the JTWC data set is generally greater than that in the STI and RSMC data sets. *Wu et al.* [2006] also found that JTWC tends to estimate higher intensities as the VMAX exceeds 51.4 m s^{-1} (100 kt). Although the VMAX in RSMC and STI data sets are generally consistent, $VMAX_{JTWC} < VMAX_{STI}$ (Figure 3a) and $VMAX_{JTWC} < VMAX_{RSMC}$ (Figure 3b) when the TC intensity is weaker than 17.2 m s^{-1}. It is also hardly explained over the different average time periods. Using ship observations, *Atkinson* [1974] found that the 10 min average wind speed was about 88% of 1 min average wind speed. Figure 3b suggests that the relationship between $VMAX_{JTWC}$ and $VMAX_{RSMC}$ is not linear as suggested by *Atkinson* [1974].

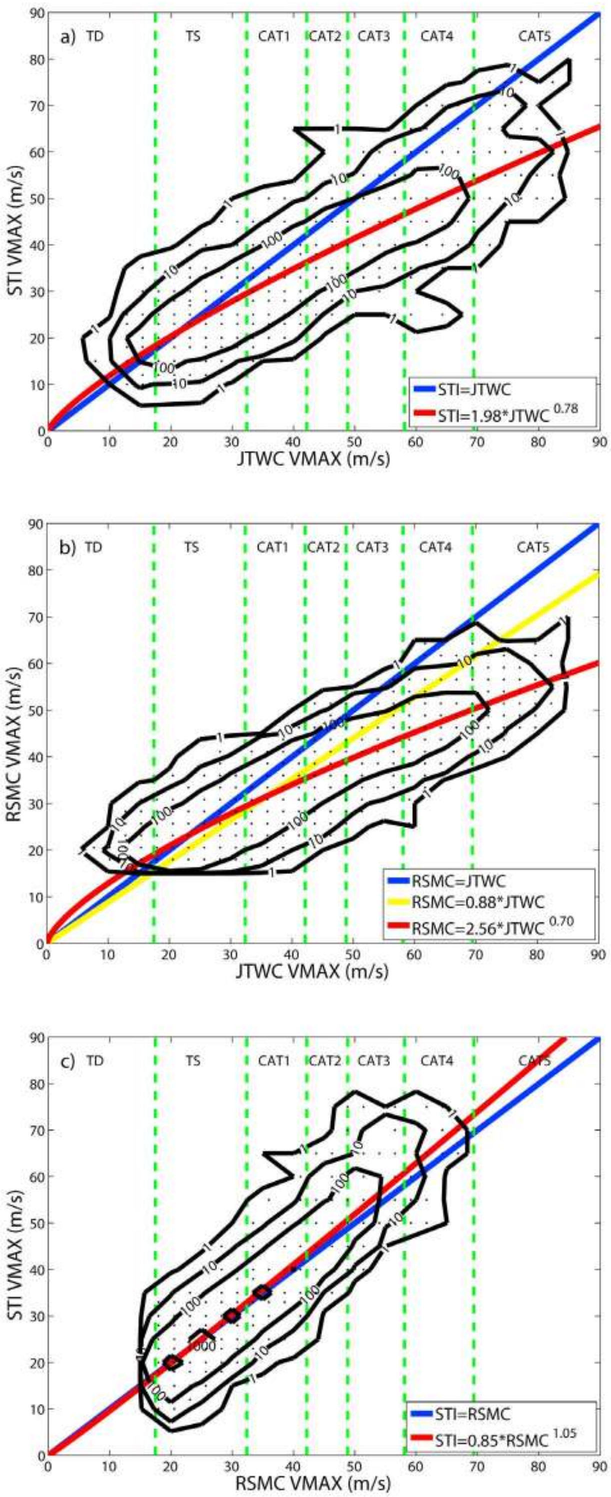

Figure 3. Scatter diagrams of (a) $VMAX_{JTWC}$ and VMAX-STI, (b) VMAXJTWC and $VMAX_{RSMC}$, and (c) $VMAX_{RSMC}$ and $VMAX_{STI}$, derived directly from the 1977–2007 concurred-TCs. Red lines are the nonlinear best fits, which are statistically significant at the 0.05 level based on *F* tests. The blue diagonal lines indicate that the two intensities are equal. The yellow line refers to the *Atkinson* [1974] relationship, which reads $VMAX_{RSMC} = 0.88 \times VMAX_{JTWC}$.

[15] Because of the difference in intensity among the three TC data sets, the concurred-TCs can be categorized into different Saffir-Simpson scales. Here we use Typhoon Fengshen (2002) and Tropical Storm Levi (1997) as examples (Figure 4). When Fengshen reached its peak intensity, $VMAX_{JTWC}$ was 72.5 m s^{-1}, which was 19.0 m s^{-1} greater than both $VMAX_{STI}$ and $VMAX_{RSMC}$. During the period 17–23 July, $VMAX_{JTWC} > VMAX_{STI} > VMAX_{RSMC}$. As a result, Fengshen was categorized into category 5 in the JTWC data set but only category 3 in the RSMC and STI data sets. In contrast, the intensity of Tropical Storm Levi is nearly the same in all three data sets. The intensity differences are less than 5 m s^{-1}. All of the concurred-TCs in individual Saffir-Simpson categories from 1977 to 2007 are examined (figures not shown). In agreement with the analysis of Typhoon Mark (1995) by *Lander and Guard* [2006], the largest intensity difference occurs for TCs stronger than 32.6 m s^{-1}. Moreover, the more intensive TCs tend to have larger intensity differences.

[16] As another measurement of TC intensity, we also examine the difference in MSLP. Similar to the analysis of VMAX, $MSLP_{JTWC} < MSLP_{STI} \leq MSLP_{RSMC}$ for TCs stronger than 32.6 m s^{-1}, whereas $MSLP_{STI} < MSLP_{JTWC}$ and $MSLP_{RSMC} < MSLP_{JTWC}$ for TCs weaker than 17.2 m s^{-1}. On average, $MSLP_{STI}$ is 8.80 hPa greater than $MSLP_{JTWC}$, but less than $MSLP_{RSMC}$.

4. Analysis of TCs in Different Categories

[17] As discussed in section 3, a concurred-TC can be classified into different Saffir-Simpson scales in the JTWC, RSMC, and STI data sets, affecting the annual number of concurred-TCs in each category. Figure 5 shows the annual number of concurred-TCs based on Saffir-Simpson scales for the three TC data sets. For those TCs with tropical storm and category 1 strengths, year to year variability in number remained low during the period 1951–2007. Their correlation coefficients during 1977–2007 all exceed 0.8, statistically significant at the 1% level based on the *T* test. It is suggested that the three TC data sets are generally consistent for tropical storms and category 1.

[18] For TCs with the intensity scale of category 2–5, their annual frequencies show remarkable differences among the three data sets since 1977 (Figures 5c and 5d). During the period 1977–2007, the annual number of category 2–3 TCs is lower in the JTWC data sets but higher in the RSMC and STI data sets. The yearly averaged tendencies are −0.10, 0.08, and 0.08 per year, respectively. On the other hand, for category 4–5 TCs, their annual number is higher in the JTWC data set by 0.16 per year, but lower in the RSMC (−0.10 per year) and STI (−0.04 per year) data sets. Consistent with our above analysis, the opposite trends strongly suggest that some category 2–3 TCs in the STI and RSMC data sets were classified into category 4–5 TCs by the JTWC data set.

[19] *Emanuel* [2005] used PDI to measure TC activity over the past several decades. In his study, the PDI was defined as the sum of the cube of VMAX for all the TCs with tropical storm strength or higher ($VMAX \geq 17.2$ m s^{-1}). Considering the opposite trends in categories 2–3 and 4–5, we calculated the concurred-TC PDI for different categories over the period 1977–2007 (Figure 6). For comparison, the PDI for all

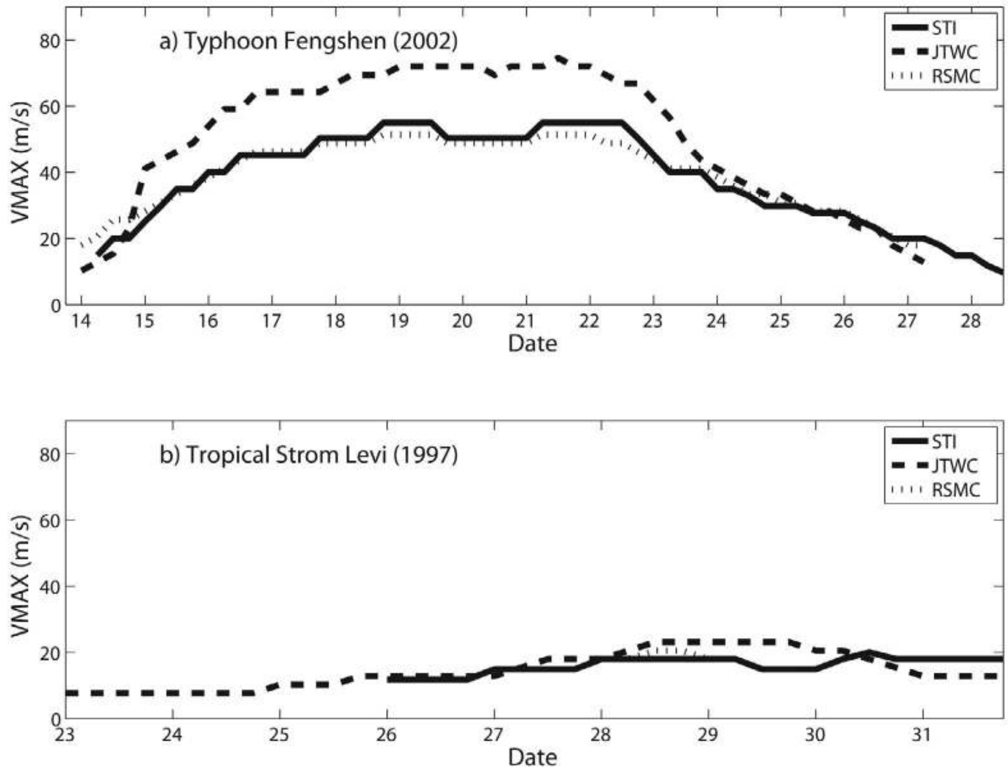

Figure 4. Time series of maximum sustained wind (VMAX) of (a) Typhoon Fengshen (13–28 July 2002) and (b) Tropical Storm Levi (23–31 May 1997). Solid, dashed, and dotted curves refer to the VMAX in the STI, JTWC, and RSMC data sets, respectively.

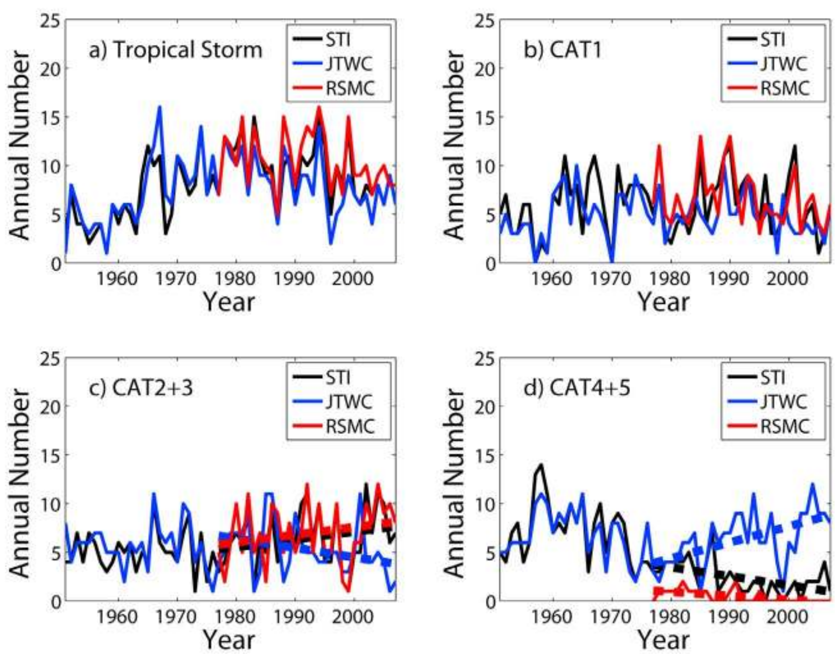

Figure 5. Annual number of concurred-TCs in 1951–2007 for (a) tropical storm (VMAX < 32.6 m s^{-1}), (b) category 1 (32.6 m s^{-1} $\leq$ VMAX < 42.2 m s^{-1}), (c) categories 2 and 3 (42.2 m s^{-1} $\leq$ VMAX < 58.2 m s^{-1}), and (d) category 4 or higher (VMAX $\geq$ 58.2 m s^{-1}). Black, blue, and red curves are for STI, JTWC, and RSMC data sets, respectively. Bold dashed lines are the trend lines in 1977–2007 for STI, JTWC, and RSMC data sets (fitted by the least squares method and statistically significant at the 5% levels based on F tests).

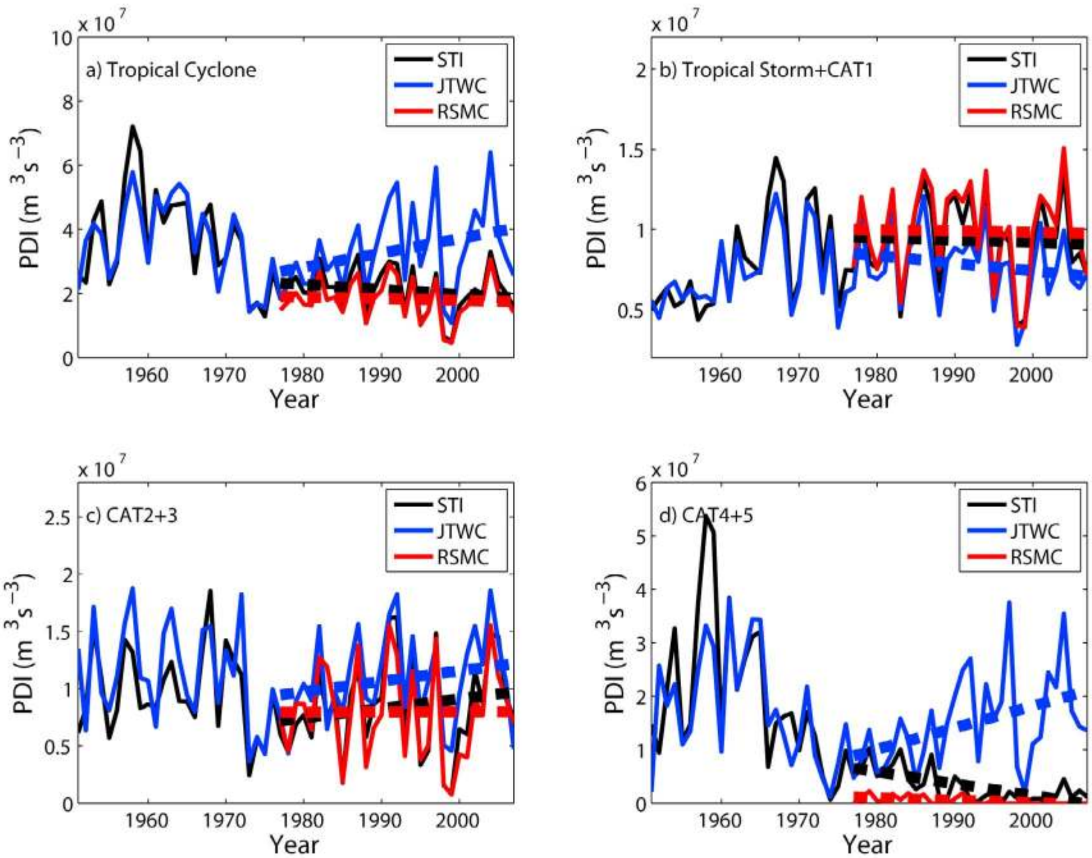

Figure 6. Time series of power dissipation index (PDI) of concurred-TCs in 1951–2007 for (a) total, (b) tropical storm and category 1 (VMAX < 42.2 m s^{-1}), (c) categories 2 and 3 (42.2 m s^{-1} $\leq$ VMAX < 58.2 m s^{-1}), and (d) category 4 or higher (VMAX $\geq$ 58.2 m s^{-1}). Black, blue, and red curves refer to STI, JTWC, and RSMC, respectively. Bold dashed lines are the trend lines in 1977–2007 for STI, JTWC, and RSMC data sets (fitted by the least squares method and statistically significant at the 5% levels based on *F* tests).

concurred-TCs is also calculated (Figure 6a). The annual PDI for all concurred-TCs in the RSMC and STI data sets decreased slightly with time, whereas it significantly increased with time in the JTWC data set. This increasing trend agrees with *Emanuel* [2005]. As shown in Figure 6b, the annual PDI for tropical storms and category 1 TCs in the JTWC data set, which slightly decreased with time during 1977–2007, is smaller than that in the RSMC and STI data sets. However, the annual PDI for category 2–5 in the JTWC data set is larger than that in the RSMC and STI data sets. In particular, the PDI for category 4–5 shows a significant upward trend in the JTWC data set, compared with the significant dowcnward trends in the RSMC and STI data sets.

[20] Since the annual PDI is also a function of TC frequency and lifetime [*Wu et al.*, 2008], we also calculated the annual accumulated lifetime for all concurred-TCs for all categories (Figure 7). The accumulated lifetime is defined as the sum of time when a TC remained in a given intensity category. Although the accumulated TC lifetime for all concurred-TCs is nearly the same in the three data sets, we do find a difference in the lifetime between the JTWC data set and the other two data sets that is very similar to those in PDI, suggesting that the difference in lifetime among the three data sets contributes to the difference in PDI shown in Figure 6. Considering the annual number difference in Figure 5, we can conclude that the PDI differences in the JTWC data set with the STI and RSMC data sets are mainly the result of the differences in intensity and lifetime in these data sets. Moreover, the fact that the JTWC data set tends to classify more category 2–3 TCs into category 4–5 TCs leads to the upward trends in the annual frequency of categories 4–5 TCs and the annual accumulated PDI, as reported by *Webster et al.* [2005] and *Emanuel* [2005].

5. Conclusions

[21] In this paper, the concurred-TCs in the JTWC, RSMC, and STI best track data sets are analyzed over the period 1945–2007 across the WNP basin in terms of the differences in track, intensity, frequency, and the associated long-term trend. The differences in the TC center position (the spherical distance) are less than 30 km, which is very small.

[22] On the other hand, great differences in TC intensity (measured by VMAX and MSLP) are found among the JTWC, RSMC, and STI data sets. Generally speaking, when

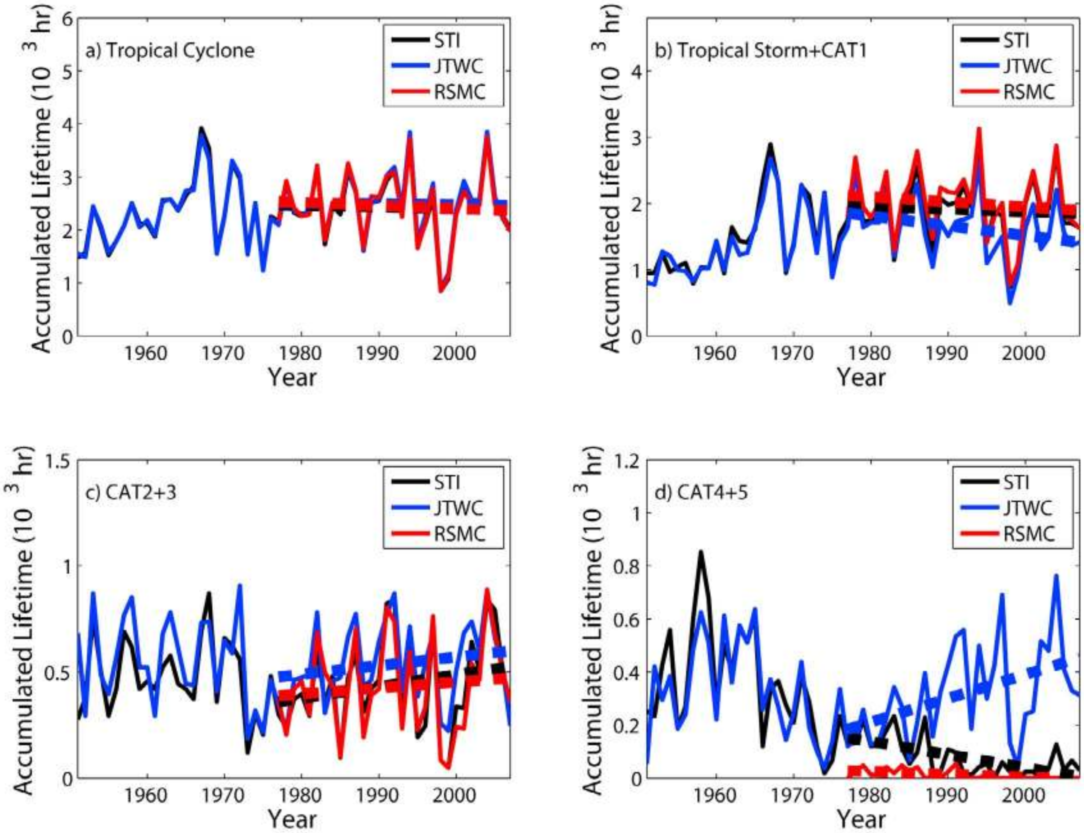

Figure 7. Accumulated lifetime of concurred-TCs in 1951–2007 for (a) all TCs, (b) tropical storm and category 1 (VMAX < 42.2 m s^{-1}), (c) categories 2 and 3 (42.2 m s^{-1} $\leq$ VMAX < 58.2 m s^{-1}), and (d) category 4 or higher (VMAX $\geq$ 58.2 m s^{-1}). Black, blue, and red curves are for the STI, JTWC, and RSMC data sets, respectively. Bold dashed lines are the trend lines in 1977–2007 for STI, JTWC, and RSMC data sets (fitted by the least squares method and statistically significant at the 5% levels based on *F* tests).

both the RSMC and STI data sets are compared with the JTWC data set, the latter shows higher intensity estimates for typhoons (VMAX $\geq$ 32.6 m s^{-1}), but lower intensity estimates for tropical depressions (VMAX < 17.2 m s^{-1}). *Atkinson* [1974] pointed out the 10 min averaged wind speed is about 88% of 1 min averaged wind speed, but this relationship is not applicable to JTWC and RSMC best track data sets. Instead, a nonlinear relationship between the intensities in the JTWC and RSMC data sets was found, namely, $VMAX_{RSMC} = 2.56 \times VMAX_{JTWC}^{0.70}$. We suggest that the differences found with TC intensity over the western North Pacific may be a result of the different algorithms used in determining TC intensity.

[23] The intensity difference can affect the annual number of intensive TCs and their potential destructiveness. In the period 1977–2007, the annual variations of tropical storms and category 1 typhoons (TYs) are similar between these data sets, but there are great differences for category 2 and higher TYs. In the JTWC data set, the annual number of category 2–3 TYs and potential destructiveness both decreased, but increased in category 4–5 TYs. These trends for concurred-TCs are consistent with that of *Webster et al.* [2005] for all the JTWC TCs. However, the trends in the RSMC and STI data sets are opposite to those in the JTWC data set. The downward trend in categories 4–5 TY annual number and potential destructiveness is significant for RSMC and STI. This trend discrepancy for concurred-TCs is similar to the results of *Wu et al.* [2006] and *Yeung* [2006] which were derived from all the TCs in the JTWC, RSMC, and HKO data sets. Given the significant differences in TC intensity in these data sets, we suggest that it is necessary to understand the underlying mechanisms responsible for TC intensity change and to further validate these data sets with observations.

[24] **Acknowledgments.** We acknowledge U.S. Department of Defense's Joint Typhoon Warming Center (JTWC), the Shanghai Typhoon Institute (STI, China Meteorological Administration), and the Regional Specialized Meteorological Center (RSMC, Japan) for providing TC data. We wish to express our sincere thanks to the anonymous reviewers for their helpful comments on an earlier manuscript. We would like to thank Kenji Kishimoto at RSMC and Zhong Yingmin at STI for helpful comments and discussions, and Peter Mayes at New Jersey Department of Environmental Protection, Trenton, New Jersey, United States, for helping us improve the grammar and language usage. This work was jointly funded by National Science Foundation of China (grants 40830958, 40730948, 90715031, 40775005), the National Grand Fundamental Research 973 Program of China (973; 2009CB421502).

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